The in-situ exploration of Jupiter's radiation belts

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Abstract

Jupiter has the most complex and energetic radiation belts in our Solar System and
one of the most challenging space environments to measure and characterize in-
depth. Their hazardous environment is also a reason why so many spacecraft avoid
flying directly through their most intense regions, thus explaining how Jupiter's radi-
ation belts have kept many of their secrets so well hidden, despite having been
studied for decades. In this paper we argue why these secrets are worth unveiling.
Jupiter's radiation belts and the vast magnetosphere that encloses them constitute
an unprecedented physical laboratory, suitable for interdisciplinary and novel scien-
tific investigations: from studying fundamental high energy plasma physics processes
which operate throughout the Universe, such as adiabatic charged particle accel-
eration and nonlinear wave-particle interactions, to exploiting the astrobiological
consequences of energetic particle radiation. The in-situ exploration of the uninviting
environment of Jupiter's radiation belts presents us with many challenges in mis-
sion design, science planning, instrumentation, and technology. We address these
challenges by reviewing the different options that exist for direct and indirect obser-
vations of this unique system. We stress the need for new instruments, the value
of synergistic Earth and Jupiter-based remote sensing and in-situ investigations, and
the vital importance of multi-spacecraft in-situ measurements. While simultaneous,
multi-point in-situ observations have long become the standard for exploring elec-
tromagnetic interactions in the inner Solar System, they have never taken place at

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Jupiter or any strongly magnetized planet besides Earth. We conclude that a dedicated multi-spacecraft mission to Jupiter is an essential and obvious way forward for exploring the planet's radiation belts. Besides guaranteeing numerous discoveries and huge leaps in our understanding of radiation belt systems, such a mission would also enable us to view Jupiter, its extended magnetosphere, moons, and rings under new light, with great benefits for space, planetary, and astrophysical sciences. For all these reasons, in-situ investigations of Jupiter's radiation belts deserve to be given a high priority in the future exploration of our Solar System. This article is based on a White Paper submitted in response to the European Space Agency's call for science themes for its Voyage 2050 programme.

1 Introduction

1.1 Why explore planetary radiation belts?

Radiation belts are the regions of a magnetosphere where high energy charged particles, such as electrons, protons, and heavier ions, are trapped in large numbers. All planets in our Solar System that are sufficiently magnetized (Earth, Jupiter, Saturn, Uranus, and Neptune) host radiation belts [92, 95]. Radiation belts are not the only regions that high energy particles can be observed; they can be found throughout a planetary magnetosphere, in the heliosphere, or the astrospheres of stars, in astrophysical objects such as brown dwarfs, and in the interstellar and intergalactic medium. Many of the environments where energetic particles are found cannot be replicated in the laboratory. Even measuring particle radiation in space is not by itself sufficient to understand its origins: For instance, while we have constrained many properties of Galactic Cosmic Rays (GCRs), the highest energy particles that we can measure, their acceleration sites are inaccessible for in-situ studies.

Radiation belts offer the opportunity to perform ground truth measurements for a variety of high energy physics processes. Apart from containing the energetic particles which we can measure in-situ, they also host most mechanisms that accelerate these particles from low to high energies in a small enough region and over time scales that can be fully monitored with space missions. These processes are explored in conjunction with additional in-situ particle and fields measurements (plasma, magnetic, electric fields, electromagnetic waves) or close-proximity remote sensing observations, such as Energetic Neutral Atom (ENA) imaging [23, 93, 144, 158]. These observations, which are critical for understanding the production and dynamics of particle radiation [177, 178], are similarly challenging to constrain for astrophysical systems. In that sense, planetary radiation belts can be seen as laboratories for in-situ, high energy astrophysics.

The strong links between radiation belts and their host planet further advocate their exploration. Radiation belt particles are modified by the accumulated effects

of the planetary neutral environment with which they interact: The properties of planetary exospheres, rings and moon-generated neutral torii are regularly studied through energetic particle measurements, particularly in extraterrestrial systems [38, 76, 78, 100, 118, 135]. The reverse path, i.e. the impact of the radiation belts on different components of a planetary system, is also important: Surface sputtering or physical and chemical alteration of moon surfaces are among several fundamental consequences of such an interaction [123, 128, 131, 134].

Radiation belt measurements have been performed at all the planets hosting them. The terrestrial radiation belts, studied since the beginning of the space age, are the best understood in terms of structure, origin, and dynamical evolution [10]. However, detailed observations of other planetary radiation belts show us that not one of them can be used as a prototype for all others [139]. Generalizing our understanding of how radiation belts work requires that we realize the different ways through which particle acceleration and loss processes can be coupled in any particular magnetospheric environment.

In that respect, measurements in the radiation belts of Uranus and Neptune, sampled only once by the Voyager 2 spacecraft, should definitely be part of any future attempt to explore the two planets [52, 74]. Saturn's radiation belts were surveyed in depth thanks to the 13-year Cassini mission at the Kronian system [139]. In comparison, Jupiter's radiation belts, while visited by numerous missions and monitored for decades through their synchrotron emission [65], still hold onto many of their secrets. No single mission, payload, or observation campaign was ever designed to capture and/or cope with their full scale, complexity, dynamics, and energetics, as argued in the two follow-up subsections.

1.2 The uniqueness of Jupiter's radiation belts

Jupiter's radiation belts are contained within the planet's magnetosphere, formed by a magnetic field that is 20000 times stronger than Earth's. Jupiter's fast rotation and material from Io's volcanoes that fills the system aid the magnetic field to push against the solar wind even further leading to a magnetosphere of enormous dimensions [5]. Within this giant system, the radiation belts grow into one of the most hazardous regions of our Solar System, trapping charged particles of extreme fluxes and energies that are typical for GCRs (Fig. 1). Unlike the radiation belts of Earth and Saturn that are limited in their extent [55, 144], substantial fluxes of energetic particles fill Jupiter's magnetosphere until the magnetopause [79]. Energetic electrons leaking into the solar wind are so intense that they overwhelm the <10 MeV GCR electrons inside ∼10 AU from the Sun, despite Jupiter being a point source in the vast heliosphere [137].

Jupiter's magnetic field is so strong that even ultrarelativistic, ∼100 GeV protons can be trapped near the planet, over 50 times higher in energy than at Earth [15, 154]. Most importantly, observations and theory dictate that processes which may populate the radiation belts with ultrarelativistic particles do exist: Jupiter's inner radiation belts contain electrons with energies in excess of 70 MeV [17, 35, 56], possibly even above 100 MeV based on model predictions [120]. These electrons emit intense synchrotron radiation which can be detected with radio telescopes. This is
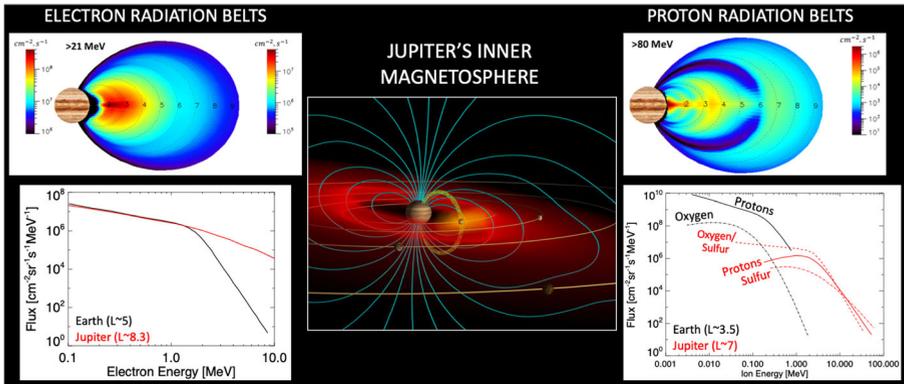
Fig. 1 Jupiter's magnetospheric region hosting the inner radiation belts (center). The moons Io, Europa, Ganymede, and Callisto are drawn, while the Io plasma torus and associated plasma disc are shown in red (Image Credit: John Spencer). Information on the inner electron and ion radiation belts are shown on each side. Color radiation belt maps are from models in [117], used with permission from Quentin Nénon. They cover the distances inward of Europa and are in part discussed in [120, 122]. The synthetic spectra are based from data in [92, 95]

one of Jupiter's most useful and unique qualities from an observational perspective, since a global picture of the most intense part of the belts can be seen remotely. Furthermore, data from the Juno spacecraft, currently orbiting the planet, reveal sites at locations remote from the radiation belts, where electron acceleration to MeV energies is regular and impulsive [19, 32, 98, 129], indicating that charged particles can gain significant energy well before reaching low jovian altitudes.

Jupiter's belts have a distinctively large variety of ions in comparable abundance to protons [2, 51] (Fig. 1, right). At other planets, ions at many MeV/n are typically trace elements. Heavy energetic ions at Jupiter, such as oxygen and sulfur, originate primarily from its moons through volcanism or particle sputtering. At lower abundances, ions like helium, sodium, magnesium, carbon, and iron, have also been measured. Furthermore, some of the ions have a range of charge (ionization) states [28, 40, 151]. This zoo of particle species and charge states evolving across very broad energy ranges, plasma, magnetic field, and wave environments within the magnetosphere, render Jupiter into an unparalleled physics laboratory for testing theories of charged particle transport and non-adiabatic acceleration and losses [113, 120, 122].

Jupiter's magnetosphere is peppered with moons and rings which sculpt the radiation belts by absorbing energetic particles, thereby obstructing their transport and energization. Energetic particle scattering into the atmosphere through waves generated by a moon's electrodynamic interaction with the magnetosphere, as also seen at Saturn [145], can have similar effects [130, 165]. Under certain conditions, moons may instead drive charged particle acceleration, mimicking the coupling that may exist between exoplanets and their host astrosphere [157]. The presence of moons within the radiation belts is thus all the more interesting. Studying how the perturbations they generate on energetic particle distributions evolve within the magnetosphere and why moons seem to affect certain species and energies more than

others (Fig. 1), we can gain valuable insights into the belts' complex dynamics [66, 122, 151]. Radiation belt measurements probing physical properties of Jupiter's faint rings, that are challenging to obtain by other means, is another important application [121]. Jupiter is also considered as the closest analogue for pulsar and brown dwarf magnetospheres that could host radiation belts [70, 109, 175] (see also Section 4.4).

1.3 Observational challenges and missing links

From the missions that have been or are being used to gain insights into Jupiter's radiation belts (Table 1), none was designed to investigate all elements of this multi-component system in a comprehensive way. To minimize radiation exposure, spacecraft orbits or operations are often planned in ways that avoid the belts' core region where extreme levels of particle radiation are expected [136]. This region is roughly located inward of Io's orbit at $\sim$5.9 R_J and at low magnetic latitudes (1 R_J = 71492 km, a jovian radius). Pioneer 10, Pioneer 11, and Voyager 1 reached deeper than Io, offering just brief snapshots of the belts from their flyby trajectories. Only few of Galileo's 34 orbits had their periapsis inward of Io's distance. Future missions JUICE and Europa Clipper will not reach deeper than Europa's orbit at $\sim$9.4 R_J.

For many past spacecraft that passed through the inner radiation belts (even at distances outward of Io's orbit), their instruments suffered from saturation and/or radiation damage, rendering part of their data unusable or very challenging to calibrate [50, 171]. Juno, the only spacecraft currently passing through the inner belts repeatedly, has instruments responding to <1 MeV electrons and <10 MeV/n ions [96]. At higher energies (e.g. >10 MeV electrons), particles are identified through the noise they create on instruments like cameras [12, 13]. These measurements offer unique insights into the structure of the planet's high-latitude radiation belts but are limited in energy or angular resolution. Energetic particle detectors on Galileo or earlier missions (e.g. [173]), were similarly constrained in terms of energy resolution above a few MeV for electrons or $\gtrsim$40 MeV/n for ions.

Energy and direction-resolved measurements are key for radiation belt studies as demonstrated by many published works for Earth and Saturn [126, 156, 164] or Jupiter (e.g. below 1 MeV for electrons) [28, 75, 97]. Much of the electron physics at Earth and Saturn, for instance, are contained below few MeV (e.g. [9]). At Jupiter, much higher energies, which are hard to resolve, are equally important. Measurements of wave properties (e.g. chorus, Z-mode) and plasma distribution functions which impact the belts' dynamics are also limited, particularly close to the planet [107, 113], although the Juno mission is already filling some gaps from its high-latitude orbits that would also enable several deep radiation belt crossings until 2025.

Table 1 lists Earth-based observation methods that offer context information for Jupiter's radiation belts. Synchrotron emissions, currently available also from the vantage point of Juno [146], offer global views for Jupiter's electron belts, but achieve little in terms of energy resolution and provide no data on energetic ions. Monitoring of the Io plasma torus, a product of the moon's volcanic activity, offers insights about magnetospheric flow fields which control the circulation of radiation belt particles [65, 115], but only where the torus is present.

Table 1 List of past, ongoing, and future missions to Jupiter's magnetosphere and radiation belts

Space missions

Mission	Type	Time	Energetic particle measurements and constraints
Pioneer 10/11	Flyby	1973-1974	Several energetic particle detectors, saturation
Voyager 1/2	Flyby	1979	problems for protons, electrons, radiation damage
Ulysses	Flyby	1992	Several energetic particle detectors, many switched off at Jupiter to avoid radiation damage
Galileo	Orbiter, Atmosphere Probe	1996-2003	Many orbits through the equatorial belts, mostly >5 R_J several energetic particle detectors, data rate and saturation problems, radiation damage. Limited data from the atmospheric probe
Cassini	Flyby	2000-2001	Distant flyby, synchrotron belts monitored by radar experiment, distant ENA imaging
New Horizons	Flyby	2007	Did not cross into the radiation belts' core, only energetic ions below $\sim$1 MeV(/n)
Juno	Orbiter	2016-2025	Energetic particle detector, relativistic electrons by monitoring noise in cameras, microwave measurements Inner radiation belt crossings over a wide latitude range.
JUICE	Orbiter	2031-2035	Mostly >15 R_J, energetic particle detectors (<1 MeV), radiation monitor (<40 MeV electrons, <250 MeV protons), ENA imagers
Europa Clipper	Orbiter	2030-2034	>9 R_J, dosimeters, charge monitors for high energy particles

Other observation modes

Type	Example observatories	Characteristics and constraints
Synchrotron Emissions, X-rays	LOFAR, GRMT, VLA	<50 MeV electrons
Aurora (UV, IR, X-rays)	Hubble, XMM-Newton, Chandra, IRTF	Monitoring energetic electrons (<1 MeV), Heavy ions
Io torus remote sensing (UV, X-rays)	HISAKI	Monitoring large-scale flows, Io volcanism, torus composition

Some constraints and challenges with respect to radiation belt measurements are indicated. Examples of remote sensing measurements with direct or indirect relevance to the jovian radiation belts (not exhaustive list) are also indicated at the lower rows. The capability for electron radiation belt monitoring with X-rays is a recent development [125]

It is clear that remote sensing observations may capture only a small fraction of the big picture. In-situ (ground-truth) observations of the radiation belts are the best way to study them, link their smallest scales to the largest, and understand their structure, origin, and dynamics. However, even with the highly anticipated scientific measurements by ongoing and future Jupiter missions in mind, a follow-up mission that aims for a dedicated and detailed in-situ investigation of the planet's radiation belts is necessary to offer closure to existing or emerging open questions. The outstanding

science that can be performed in Jupiter's radiation belts, discussed in Section 2, justifies why such an endeavor deserves to be assigned as a high priority target in ESA's Voyage 2050 programme.

2 Outstanding science in Jupiter's radiation belts

Scientific investigations in Jupiter's radiation belts are well linked to three of the four overarching themes of ESA's ongoing Cosmic Vision programme, which should be relevant also for the Voyage 2050 cycle. These links are traced in Table 2 and exemplified in Sections 2.1–2.6.

2.1 Adiabatic electron heating vs local electron radiation belt sources and losses

State of the art and open questions Despite decades of research on how low energy electrons are accelerated to the very high energies observed in Jupiter's radiation belts, many fundamental questions remain open. Similar to Earth [62, 68, 181], two main modes of acceleration are considered: Adiabatic heating and local acceleration of electrons by nonlinear interactions with electromagnetic waves. The challenges involved in separating the two contributions arise from the fact that they overlap in time, space, and energy. In addition, the same processes may induce particle and energy losses. For example, whistler-mode chorus waves can either energize electrons through energy diffusion or scatter them into the atmosphere through pitch angle diffusion. Whether a process acts as a source or a sink depends on the background space environment which defines the energies, pitch angles, and regions that resonant interactions occur. Figure 2 summarizes our current view on how certain interactions in Jupiter's electron radiation belts (e.g. scattering) are distributed in L-shell and energy and which magnetospheric mechanism is their driving force.

Adiabatic heating, i.e. the energization of electrons through inward transport towards stronger magnetic fields, can be facilitated by at least three mechanisms:

Table 2 Jupiter radiation belt science and the links to ESA's Cosmic Vision themes

ESA Cosmic Vison 2015-2035	Relevant overarching scientific questions for Jupiter's radiation belts	Specific science goals (Subsections)
How does the Solar System work?	Why are Jupiter's belts so intense and its magnetosphere such a powerful accelerator?	2.1, 2.2, 2.3, 2.4, 5
What are the fundamental physical laws of the Universe?	What can we learn for high energy plasma physics by studying different planetary radiation belts?	2.1, 2.2, 2.3, 2.4, 2.5
What are the conditions for planet formation and the emergence of life?	What are the astrobiological implications of charged particle radiation in Jupiter's mini Solar System and especially Europa?	2.1, 2.2, 2.3, 2.6
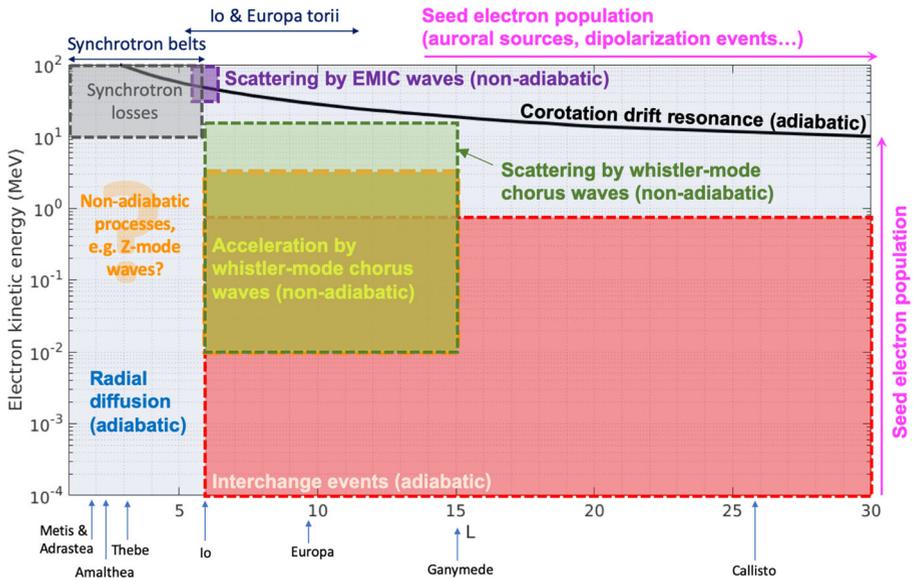
Fig. 2 A summary of processes contributing to electron transport, acceleration, and losses in Jupiter's radiation belts as a function of L-shell (magnetic equatorial distance) and energy, as we understand them today. "EMIC" refers to Electromagnetic Ion Cyclotron waves

(1) energy independent radial diffusion induced by low frequency magnetic field fluctuations possibly driven by variable thermosphere winds [22, 120], (2) interchange injections [41, 88], and (3) transport due to variable convective electric fields, such as the dawn-dusk electric field [115]. The latter refers to a strongly energy dependent mechanism, with high efficiency for 10-100 MeV electrons that drift slowly in magnetospheric local time ("corotation drift resonance") [141]. Existing physical radiation belt models assume an energy independent radial diffusion as available measurements cannot adequately constrain the other two processes, especially above 1 MeV. Resolving the energetic electron distribution function [164] is necessary for separating overlapping adiabatic processes with a distinct energy dependence (Fig. 2). Transient phenomena (e.g. interplanetary shocks) may also mediate adiabatic transport, but are discussed in Section 2.5.

The occurrence of resonant wave-particle interactions has been observed around Jupiter primarily by Galileo and in the extended disc of plasma outward of Io's orbit [107, 157]. Inward of Io the space environment may also be favorable for wave-driven acceleration, but its properties are less constrained [113]. Other wave types which are not as important at Earth, such as Z-mode, may have a strong impact at the giant planets, as Saturn-based research shows [179]. The radiation belts inward of Io are a prime candidate for Z-mode acceleration of electrons [108]. These inner belts are also the only place in the Solar System where we can investigate in-situ the impact of synchrotron energy losses [36]. The production of synchrotron radiation not only affects the energy of the electrons but determines how far in latitude they can execute

their field-aligned bounce motion, limiting in this way the wave populations they can interact with.

Key measurements and justification Figure 2 shows how any given physical process may generate a seed electron population for another to take over. Adiabatic heating may provide electrons in the appropriate energy range and L-shell where waves would accelerate them further, and vice-versa. Processes thus complement each other and are best studied in unison. In that respect, plasma moments and composition, electromagnetic wave properties (frequency, power, polarization, wave normal angle), energetic electron spectra and their spatial distribution need to be resolved. While Juno, JUICE, and Europa Clipper will bridge several existing gaps in spatial coverage [71, 90], low and mid-latitudes and a wide local time range inward of Europa would need to be surveyed. The wave frequency coverage should extend at least until up to the upper-hybrid range, such that the whistler and Z-modes are resolved at any distance, including very strong magnetic field regions near the planet. Electron measurements should be directional and energy-resolved well beyond $\sim$1 MeV. The signature of corotation drift resonant transport could extend up to $\sim$100 MeV, for instance. Observations over extended time should help define the nominal configuration of Jupiter's electron belts.

2.2 Cosmic Ray Albedo Neutron Decay as universal proton radiation belt source

State of the art and open questions Galactic Cosmic Rays (GCRs) with a sufficient energy to overcome the barrier of a planetary magnetic field may collide with a planet's atmosphere and rings [79]. The secondary neutrons produced by these collisions can travel away from their generation site until they β-decay to protons and electrons. If this happens in a material-free region of the magnetosphere, the decay products become trapped and add to the planet's radiation belts. This process, termed
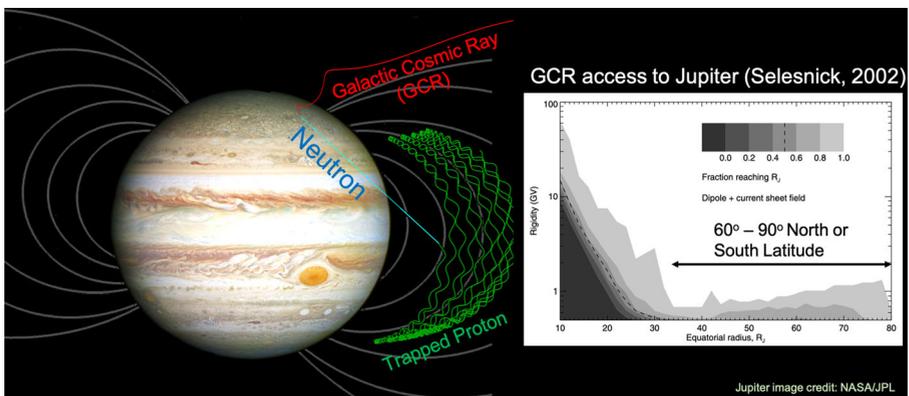
Fig. 3 The CRAND concept on Jupiter and GCR cutoff rigidities in Jupiter's magnetosphere [149]. The approximate latitude range on the planet (added by the authors) that <1 GV GCRs arrive (<0.43 GeV protons), is based on field mapping in http://www.igpp.ucla.edu/people/mvogt/mapping/

Cosmic Ray Albedo Neutron Decay (CRAND – Fig. 3), supplies and maintains the radiation belts of Earth and Saturn with protons of energies between several MeV and up to the proton trapping limit of each planet in the GeV range [33, 67, 77, 140, 150]. Earth and Saturn have weaker magnetic field strengths compared to Jupiter that allow a significant part of the GCR spectrum to reach them, and material targets that can generate considerable fluxes of secondary neutrons (Earth's nitrogen/oxygen atmosphere, Saturn's icy rings). Jupiter, instead, has a hydrogenous atmosphere, tenuous rings, and a much stronger magnetic field. This different parameter regime is suitable for testing whether CRAND-driven proton radiation belts are a component of any large-scale magnetosphere or if their presence depends strongly on the unique properties of a planet and its magnetosphere.

Existing observations, with proton spectra limited below ∼80 MeV, do not provide any conclusive evidence: Such protons likely originate through inward adiabatic transport from a distant source [122]. Jupiter's innermost radiation belts (r<6 R_J), where very energetic protons from CRAND may get more easily trapped, are being and will be sampled extensively only by Juno. Juno, however, cannot resolve the energies of protons above 100 MeV, even if the instrument noise they create is recorded [12]. JUICE and Europa Clipper will not reach inward of Europa's orbit and will not provide constraints on CRAND, even if RADEM, the radiation monitor of JUICE, will measure protons up to 250 MeV [133].

From a theoretical perspective, Jupiter's strong magnetic field is expected to exclude a significant part of the GCR spectrum from impacting the planet, thus restricting the production of secondary neutrons and the CRAND source rate to low values [160]. Still, that same magnetic field may form an efficient trap for CRAND protons compared to the weaker fields of Earth and Saturn. Furthermore, the GCR impact area on Jupiter is very large, while the percentage of neutrons that would decay within Jupiter's enormous magnetosphere before they escape into interplanetary space is higher than at other planets. All that could allow protons to slowly accumulate into a strong proton radiation belt despite a weak CRAND source rate. The efficiency of Jupiter's hydrogenous atmosphere in generating secondary neutrons through processes like proton-proton collisions [60] is also unknown. This efficiency has not been possible to constrain at Saturn, Uranus, and Neptune, that possess hydrogen-rich atmospheres: atmospheric and ring sources of CRAND at Saturn are mixed and difficult to distinguish [34], while Voyager 2 never reached close enough to Uranus and Neptune where CRAND protons may be stably trapped (e.g. [161]).

Key measurements and justification Simulations predict that magnetospheric (non-CRAND) protons inward of Io drop significantly in intensity above 50-100 MeV and are confined to low magnetic latitudes [122]. This equatorial confinement becomes stronger inward of Thebe at ∼3 R_J (Fig. 1, top right). Measurements that extend the energy sampling to the GeV range and with a full pitch angle coverage would resolve CRAND protons directly, if present, given that CRAND is a process that can easily generate protons up to 10s of GeV. The ability to resolve the signature of CRAND would enable also a detailed monitoring of the dynamics of the energetic protons with a magnetospheric origin.

2.3 The enigmatic origin of the heavy and light ion radiation belts

State of the art and open questions The jovian radiation belts contain high fluxes of sulfur and oxygen, resolved mostly up to ∼40 MeV/n (Section 1.2 and Fig. 1, lower right). The relative abundances of these heavy ions to protons indicate that their origin is primarily iogenic, given the lack of any other obvious sulfur source. As Io generates these species at low energies, there have to be mechanisms accelerating them to the multi-MeV/n range observed. However, the evidence on the nature of the acceleration processes are conflicting. The limited heavy ion charge (ionization) state measurements for the suprathermal energy range and challenges in resolving the ion species at many 10s of MeV/n with existing data account for that (Fig. 4A).

Singly charged energetic ions are most relevant in acceleration models which predict that charge exchange and re-ionization reactions are important [11]. These reactions transmit charged particles from the Io torus to an extended region beyond Europa's orbit, which then supplies the ion radiation belts through adiabatic transport. Radial gradients of energetic ion fluxes [30, 59] and the abundances of >5 MeV/n sulfur and oxygen [31, 56] appear consistent with this theory. A recently discovered ion radiation belt component that includes energetic oxygen and sulfur and resides just above Jupiter's atmosphere, also requires that its ions are singly charged [75]. Theories which do not involve charge exchange and re-ionization and set no constraints on the ions' charge states, have their starting point in the enhancement of energetic ion fluxes well beyond Europa's orbit and in tail reconnection events [80, 88]. An ion heating source at 20-25 R_J, the nature of which is not understood [152], may be relevant. Indirect evidence for the presence of oxygen and sulfur with a broad distribution of charge states come e.g. from [28] through the analysis of interchange injections. [118] combine aspects of the aforementioned theories and predict that ionization states evolve with distance: Ions start as multiply charged far from Europa, gradually reducing their ionization through charge exchange as they
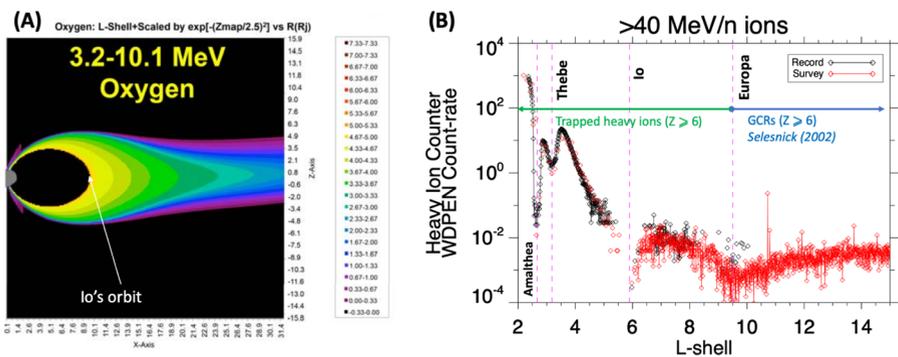
Fig. 4 (A) Integral fluxes of 3.2-10.1 MeV oxygen at Jupiter, based on an empirical radiation belt model. Figure courtesy of NASA, from [57], modified version published also in [58]. The black shaded area inward of Io's orbit is not due to missing data, but to less resolved measurements in energy and composition, shown in (B) as a mission-averaged L-shell profile of Galileo Heavy Ion Counter count-rates of >40 MeV/n ions, partly published in [149] and [56]. Moon locations are marked, matching well the signal dropouts

propagate through the Europa and Io torii. Still, [151], who reconstructed signatures of MeV oxygen and sulfur depletions seen by Galileo in the vicinity of Io, concluded that they should be fully ionized (charge states of 8 and 16, respectively). X-ray emissions from the Io torus [45] are in part consistent with fully stripped, heavy ions at MeV energies since electron stripping dominates over charge exchange in that energy range. Current estimates of MeV oxygen fluxes, however, seem too low to account for the strong X-ray signal.

At the highest observed energies, Galileo measurements inward of Io reveal a population of >40 MeV/n and $Z \geq 6$ ions which is separated from the rest of the jovian magnetosphere: A strong and persistent signal depletion is seen at Io's orbit (Fig. 4B). This implies that for >40 MeV/n heavy ion transport across Io is difficult, if not impossible. With adiabatic transport excluded, the >40 MeV/n species near the planet do not have an obvious source, unless they are supplied across the moon's barrier during extreme episodic events, missed by past spacecraft. If that is not the case, a local production or acceleration mechanism should be invoked. The difficulty to separate species precludes any definite conclusion.

The direct capture and trapping of heavy ions through charge stripping at the upper jovian atmosphere, as seen with Anomalous Cosmic Rays at Earth [153], may offer a pathway for heavy solar and GCR ions into the jovian system. Other energetic ion species that have been detected at Jupiter (sodium, magnesium, helium) can be used as additional tracers of the circulation and acceleration of iogenic or solar wind particles [56]. The spallation of the jovian rings as a possible source of energetic helium in the radiation belts [51] is another interesting possibility that has not been followed up.

Key measurements and justification The heavy ion radiation belts have multiple components that can be separated by both species and ionization state. Each component may be sensitive to different physical processes and its properties (energy spectra, L-shell, and pitch angle distributions) revealing for different aspects of Jupiter's radiation belts and magnetosphere. Many of the existing uncertainties arise from the fact that several ion charge state estimations were obtained indirectly. In terms of composition, Juno is filling many gaps for the <10 MeV/n ions [63] but these need to be extended well beyond 100 MeV/n, so as to understand how their acceleration evolves and what are its limits in energy. Ionization states at <1 MeV could still update energetic ion transport and acceleration models, in case they prove difficult to obtain for very high energies.

2.4 High latitude charged particle acceleration as a universal radiation belt source

State of the art and open questions Jupiter's plasma sheet is the extended equatorial region beyond Io's orbit that traps dense cold plasma and high fluxes of energetic particles mostly in the keV to low MeV range. The plasma sheet has been studied not only as a major component of the planet's magnetosphere, but also as an enormous storage ring of charged particles that supplies the radiation belts. A large body of research has been dedicated to the dynamics within Jupiter's plasma sheet (such

as injections and ion-neutral gas interactions, Sections 2.1–2.3), because the majority of the measurements made before the Juno mission were at low latitudes. Despite that, many aspects of its energetics are still unresolved. Several Galileo-based studies reported observations of >30 keV electron angular distributions reminiscent of high latitude auroral processes [101, 167]. Furthermore, Galileo data show the plasma sheet to contain a low but persistent population of >11 MeV electrons, with no obvious origin [79]. The connection of these equatorial observations to dynamics and phenomena at high latitudes was speculated, but the lack of in-situ data from the magnetospheric high-latitude counterparts left many questions open.

Recent discoveries made by NASA's Jupiter polar orbiting spacecraft, Juno [18], have put the spotlight on auroral processes as a means to generate high-energy ions and electrons that fill Jupiter's plasma sheet. Juno has observed intense and energetic (>1 MeV) electrons beaming upward from the planet [32, 98], energetic ion conics [27], and upward ion beams [99]. A remarkable discovery is the prevalence of upward electron beams. [97] have shown these to be a persistent characteristic of Jupiter's main auroral and polar cap regions. The energy flux contained in the upward beams is often greater than their precipitating counterparts and much greater than for electrons of similar energy in Jupiter's radiation belts. Similarly, in the polar cap region, upward beams of energetic electrons are always present in observations, suggesting active and persistent acceleration at altitudes below the spacecraft [97]. In addition, spectral features of Jupiter's UV aurora in the polar cap observed by Juno cannot be reconciled with the precipitating electron fluxes [44], hinting that interesting physics occur at lower altitudes that have yet to be explored. Before Juno, >16 MeV electrons and <0.3 keV protons generated at high latitudes were seen in Ulysses data [159]. Juno has detected similar features as bursts of >10 MeV electrons [19, 129]. It is reasonable to hypothesize that a certain fraction of all these upward moving energetic particles populate Jupiter's plasma sheet and later end up via inward radial diffusion or injections into the radiation belts (Fig. 5). Similar hypotheses have been put forward for the MeV electrons produced impulsively over a large region of Saturn's high latitude magnetosphere [143], and for energetic particles from Earth's cusp [53], attesting to the possibility of high magnetospheric latitudes being an important radiation belt source, common to strongly magnetized planets with a dense atmosphere.

Key measurements and justification High-latitude auroral acceleration is a constant source of high-flux, field-aligned energetic ions and electrons. The exact details of the particles' fate are unknown and only now are theoretical ideas starting to emerge on their origin [44]. It remains unclear if, how, and what percentage of the auroral particles convert from field-aligned to trapped, populate the plasma sheet and, subsequently, the radiation belts. The equatorial counterparts of the high-latitude events may be studied partly by JUICE. Still, both JUICE and Juno offer limited information of the highest energy particles as spectral information goes to a few MeV and lacks energy resolution above that. Energy-resolved measurements extending to higher energies would constrain the spectral shape of the high latitude sources, determine if there is an upper limit in the acceleration for both ions and electrons, and allow us to compare if the belts' seed population shares common properties with the high latitude accelerated products. Simultaneous observations in plasma, magnetic
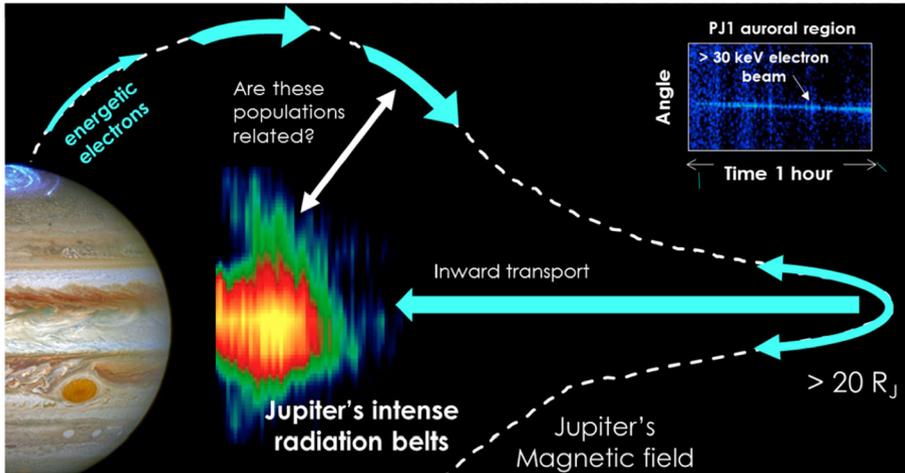
Fig. 5 The concept of high-latitude electron sources evolving into radiation belt populations. Courtesy: George Clark (JHUAPL)

field, electric field, and waves could be revealing about the origin of the acceleration mechanisms [29, 105].

2.5 The space weather of Jupiter's radiation belts

State of the art and open questions Similar to the magnetosphere that encloses them, Jupiter's radiation belts are very dynamic. This variability, i.e. the radiation belt's space weather, is important to assess for two reasons. Firstly, different physical radiation belt processes which may be difficult to distinguish in average profiles, can be resolved through their distinct variability time scales. Studies for Saturn's proton belt dynamics, for instance, have been central for understanding their CRAND-related origin [77, 140, 142]. The second reason is that there are physical interactions that are responsive to changes in a local radiation belt environment, such as surface sputtering creating transient satellite exospheres [110].

Most of our information for time variations in Jupiter's radiation belts comes from monitoring the synchrotron emissions by their MeV electrons. These reveal changes at different time scales, ranging from days to years. The longest-term changes seem to have a two-year lagged response to the solar wind [35, 37, 54, 147]. It has been argued that this time lag is explained by slow radial diffusion of electrons which is mediated through a solar-wind modulated dawn-dusk electric field that has been observed near Io's orbit [65, 115]. If this model is correct, radiation belt transients should evolve the fastest for 10-100 MeV electrons (Fig. 2, "corotation resonance"). Such rapid enhancements in >11 MeV electron data were observed in Galileo data [141], but the lack of energy resolution for these measurements, prevents any definite conclusion. How the solar wind transmits changes in the dawn-dusk electric field at Io is also unknown, in part because instantaneous solar wind parameters upstream of Jupiter come from models propagating measurements obtained at 1 AU to the planet's

heliocentric distance at 5.2 AU. Furthermore, the dawn-dusk electric field has never been detected in-situ, in plasma flows, or electric field measurements [7]. An in-situ detection could verify if this convective field extends inward or outward of Io's orbit and indicate the spatial scales over which it exerts control on the radiation belts.

Regular, short-term variations in the synchrotron belts (∼days) have been observed in response to solar EUV flux changes, supporting a theoretical link between radial diffusion of electrons from changing winds in the planet's thermosphere [22, 73, 168]. Measurement of electron spectra following EUV changes, for exploiting this link in-situ, are missing. Such measurements could peer into the physics of thermosphere-driven diffusion: Is this process energy dependent and how does it scale with L-shell? At Saturn, for instance, where there is evidence that this form of diffusion acts on its radiation belts, in-situ data show that this scaling is much steeper than theory predicts [77, 138]. The least explained variations are those on time scales of weeks, which show no obvious correlation to either EUV or dawn-dusk electric field changes [72].

For the ion radiation belts of Jupiter that cannot be resolved through synchrotron emissions, variations are poorly explored. Unlike Saturn, whose moons restrict MeV ion transport, at Jupiter this does not occur, at least below the 40 MeV/n range ([122] and Section 2.3). Communication between energetic ion populations across the moon orbits should be possible, such that variations in the middle magnetosphere may be transmitted to the innermost belts. For all species, a several day recurrence rate of tail reconnection events, which likely enhances the seed radiation belt population [84, 88], may be important. Juno findings of high latitude particle acceleration sites may also be significant, if these indeed regulate the belt's seed population (Section 2.4).

For certain ion species, the lack of variations may be revealing. For instance, since CRAND (Section 2.2) is a quasi-stable source, seeking for a steady proton signal over multiple orbits would allow to distinguish it from other, more variable sources of protons. If the population of energetic heavy ions (>40 MeV/n) is stable over even long timescales, as hinted in data shown in Fig. 4B, its source process would need to be equally invariant with time.

Key measurements and justification   Any of the aforementioned open questions would benefit from the in-situ measurements identified for all science themes discussed in Sections 2.1–2.4, collected over extended time periods to enable variability studies. Different time scales can be probed by regulating the re-sampling rate of the radiation belts, as done e.g. for Saturn with Cassini [141, 144]. Simultaneous solar wind measurements are important to obtain close to Jupiter. Capturing the global dynamics of the belts' seed population (beyond Europa's orbit), could be achieved through ENA and/or X-ray imaging. Remote sensing of the Io plasma torus, the aurora, and the synchrotron emissions of the electron belts would provide excellent context (Fig. 6).

2.6 Radiation processing of moon surface material and astrobiological implications

State of the art and open questions   Excluding Io, the surface of which is regularly altered by its ongoing volcanic activity, all other moons of Jupiter that orbit within the

magnetosphere and the radiation belts are exposed to a variety of external weathering processes that modify their physical and chemical properties. Irradiation by low and high energy charged particles is one of these processes. The radiation belt particles, which are also the most surface penetrating, can reach between several cm to several m in depth, either directly or due to the Bremsstrahlung they emit as they are decelerated in ice [123, 124]. Such interactions can transform the top layers of the surface by altering its crystallinity, its thermal inertia, or even by creating new molecules ([128] and references therein). These modifications should be considered when interpreting remote sensing observations of the moons (e.g. reflectance spectra), when surface samples are retrieved directly through a lander, or indirectly, by measuring sputtered products and micrometeoroid ejected dust grains from the surface, as it will be done with JUICE and Europa Clipper.

For Europa, where future landers could seek biosignatures in material that may have upwelled from its subsurface ocean, the study of radiation-induced surface modifications has an added value. Particle radiation can impact Europa in different ways, for example by generating the already detected H_2O_2 on its surface [24]. This oxidant may provide a source of chemical energy to sustain a biosphere in Europa's ocean [26, 169]. On the other hand, it is estimated that aminoacids, the simplest compounds to be sought as potential biosignatures on the surface, can be destroyed by particle radiation from Jupiter down to a depth of about 10 cm in Europa's equatorial region (Fig. 7) [123].

Quantifying any of the mechanisms discussed above depends significantly on the input energetic particle spectra to which a surface we assume is exposed. Particularly
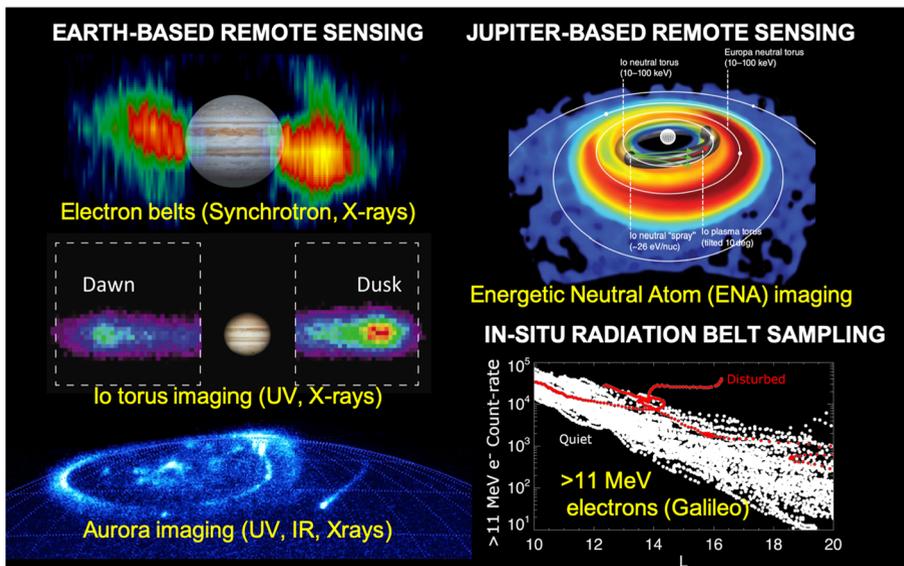
Fig. 6 The different options for space weather monitoring of Jupiter's radiation belts. Image/plot credits: synchrotron belts (NASA/JPL), torus imaging (from [115], used with permission), aurora image (NASA/STScI), ENA image simulation (from [20], used with permission), in-situ data plot based on [141]
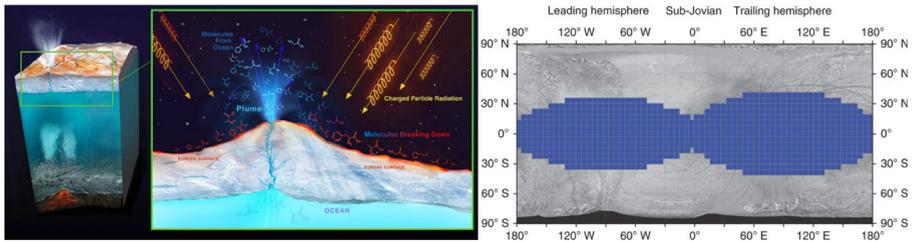
Fig. 7 (Left) Europa's surface is continuously bombarded by charged particle radiation (Image credit: NASA/JPL). The blue-shaded area (right) shows the current best estimate on where Europa's surface is radiation-processed down to ∼10 cm (from [123], used with permission)

for >1 MeV electrons and >10 MeV(/n) protons and ions, energy spectra are not as well constrained as for lower energies. Many of the relevant studies rely on arbitrary extrapolations to energies of 100s MeV(/n) or more to predict the most penetrating particles' effects. For even higher energies, it is assumed that the particle spectrum is that of GCRs that can reach into a moon's orbit [124], resulting in rather low input fluxes for most moons: in Europa's case, <13 GeV GCRs cannot reach its orbit [124, 149]. However, if processes like CRAND provide even a small input to Jupiter's radiation belts (Section 2.2), fluxes of relativistic protons can be significantly elevated from their presumed "empty" GCR levels. Proton trapping at Europa is limited at ∼2.5 GeV and exceeds 100 GeV near the planet [15]. CRAND protons would populate the spectral range below the GCR cutoff energy, up to the trapping limit.

Key measurements and justification An improved description of the energetic particle spectra would transform our understanding of how Jupiter's radiation belt environment affects the surfaces of its moons. All effects discussed here develop on timescales of thousands to millions of years, such that long-term average energetic particle spectra should be sufficient to estimate the energy flux and its long-term impact on the moons' visible surface and subsurface. The requirements for the energy range that the measurements should cover are similar to those discussed in Sections 2.1–2.5. Understanding if certain physical processes, like CRAND, contribute to the radiation belt content, would allow to physically extrapolate measurements to even higher energies than it would be possible to detect.

3 Space missions to Jupiter's radiation belts

Here we outline considerations for space missions that could explore Jupiter's radiation belts and we identify enabling technologies. Several past studies by ESA were done in the context of the JUICE mission, including its previous variants, Laplace and EJSM. Even earlier studies of relevance are those of the Jupiter Radiation Study (JURA) and a series of investigations for the exploration the jovian system by [4]. The latter were subdivided into three mission studies, the Jovian Minisat Explorer (JME), the Jupiter Entry Probe (JEP), and the Jovian System Explorer (JSE), focusing on Europa, the jovian atmosphere, and the magnetosphere, respectively. The

JUpiter MagnetosPheric boundary ExploreR (JUMPER) study is likewise relevant [43]. Appropriate points from those reports are reiterated here. Besides that, the mission scenarios discussed in Section 3.3, which are only introduced as initial concepts, deserve dedicated studies on both mission and subsystem levels.

3.1 Scientific design drivers

Spatial coverage Studying the radiation belts requires to monitor them as part of the jovian magnetosphere. Spatial coverage should be maximized in terms of distance (from the planet to the magnetopause), latitude, and local time, similar to what Cassini achieved at Saturn or Juno is currently doing at Jupiter. Should that not be possible, the least explored regions should be prioritized, i.e. the radiation belts' core between the planet and Io at low and mid-latitudes. In terms of local time, strong asymmetries are expected between the dawn and dusk magnetospheric sectors based on remote sensing observations (e.g. [115]). Day-night asymmetries cannot be resolved by Earth-based observations, but may be constrained by Juno (e.g. [146]), and based on future findings, priorities for local time coverage should be modified accordingly.

Temporal coverage The radiation belts evolve on a variety of timescales, the longest ones in the order of a few years. The minimum lifetime of a single mission to Jupiter's belts should be about 2 years. Resolving shorter time scales (weeks/months) could be achieved through radiation belt crossings with a similar frequency. For even shorter time scales and for separating temporal from spatial variations, multi-point, in-situ measurements in the magnetosphere and the synergy between remote sensing and in-situ observations are key. Remote sensing may be offered through Earth-based observatories (e.g. synchrotron observations – Table 1, Fig. 6) or from Jupiter, at a wide range of wavelengths as well as in ENAs.

Instrumentation While the radiation belts are described by their energetic particle distributions, their origin, structure, and dynamics are best understood through complementary investigations of their space environment in plasma, magnetic field, electric field, and waves at a wide frequency range (Sections 1, 2). Table 3 marks which type of instruments are relevant for different investigations. The properties for the particles and fields suite of Juno, JUICE, Europa Clipper, and the Van Allen Probes [18, 61, 162], offer excellent analogues for the requirements of similar detectors in a mission to the radiation belts. An added measurement capability should be that of energetic ion charge states, as done with the CHEMS instrument on Cassini [81]. Among the instrument types listed in Table 3, the most novel would be those for detecting (ultra)relativistic particles. Extending energy and direction resolved measurement capabilities to ∼100 MeV electrons and ∼1 GeV(/n) ions, in order to comply with expectations for the energies of trapped populations in Jupiter's radiation belts, has never been attempted in a planet other than Earth or the solar wind around 1 AU, where large detectors, mostly aiming at low flux GCRs, have been or are being operated (e.g. [132]). Measurements of particle distributions for all energies requires 4π sky coverage for ions or full pitch angle coverage for electrons, such

Table 3 Science questions (Section 2), relevant instruments and observation modes

	Plasma	Magnetic field	Electric field	Waves	Energy particle		ENA and/or X-Ray imaging	Solar wind in-situ	Earth-based monitoring
					Non-relativistic	Relativistic			
Electron radiation belts (2.1)									
CRAND protons (2.2)									
Ion radiation belts (2.3)									
High latitude sources (2.4)									
Space weather (2.5)									
Moon surfaces (2.6)									

Green color indicates relevance

that a spinning spacecraft is preferred over a three-axis stabilized one. A spinning spacecraft may have additional advantages for instrument design (Section 3.4).

3.2 Technical design drivers

While there are numerous technical design drivers, below we focus on those with unique aspects for a mission to Jupiter's radiation belts (mass, radiation, communications, planetary protection). Discussion about parameters such as power, thermal constraints, spacecraft autonomy are addressed in past Jupiter mission studies.

Mass The payload masses for Juno, JUICE, and Europa Clipper are ∼170, ∼220 and ∼350 kg respectively [18, 39, 46, 116], with typically less than 40% allocated for in-situ particles and fields instrumentation and ENA imagers. While that appears to imply significant extra mass for accommodating improved and new instruments for a dedicated space physics payload, the available margin may be significantly smaller: The required, multiple crossings through the radiation belts translate to heavier radiation shielding. The possible use of instruments with strong magnets may also require additional material for magnetic shielding (Section 3.4). The need for solar wind monitoring and multi-point in-situ measurements implies mission designs with at least two orbiting spacecraft, setting tight mass constraints for the case these have to be accommodated in a single launcher. From earlier mission studies [4, 43], the minimum mass of a second, small orbiter would be in the range of 100 kg. Payload distribution among the different spacecraft, orbit, instrument, and shielding design are parameters that need to be iterated for maximizing payload mass and optimizing science return.

Radiation For each of its few orbits through the inner radiation belts the Galileo spacecraft was accumulating 30-40 krad per crossing behind an equivalent shielding of 2.2 g/cm^2 aluminum [3, 50], in agreement with estimates from radiation belt models [136]. At the center of the radiation belts core, the same models estimate dose rates that can be as high as 200 or 100 krad/day behind 2.2 or 5.0 g/cm^2 aluminum, respectively. This means that within several orbits, a spacecraft crossing through the innermost radiation belts core with a shielding below 5.0 g/cm^2 would accumulate an equivalent dose as Galileo during its 6.5 years and 34 orbits mission. Clearly, much heavier passive shielding than 5.0 g/cm^2 would be required. On the other hand, given the unavoidable constraints in mass, radiation mitigation strategies should also iterate orbit design, spacecraft and instrument shielding distribution, instrument and subsystem accommodation and aim for the development and use of radiation-hard electronics, to minimize radiation dose accumulation per orbit, to extend subsystem tolerance and overall maximize mission lifetime and the number of radiation belt crossings. Heritage from past missions and particularly the measurements and operations of the Juno spacecraft, that is repeatedly crossing through the inner radiation belts, would be valuable for defining radiation mitigation strategies.

Communications In the case of a multi-spacecraft mission the options for autonomous (Earth-direct) vs intra-spacecraft (relay) communications should be

examined as they impact orbit and spacecraft design. Direct-to-Earth communications likely allow for higher flexibility and autonomy to each spacecraft for science operations. A relay offers the option of longer storage and downlink periods of large volume of high-quality data [4].

Planetary protection Europa's surface or immediate subsurface (see Section 2.6) may be hosting biosignatures associated to the subsurface ocean below its crust, and thus planetary protection considerations are relevant, especially for a mission that may cross the moon's orbit and a spacecraft that is subject to risks imposed by very high radiation exposure. In terms of orbit, the design should minimize the possibility of an accidental impact with the moon. In the study for the Jovian Minisat Explorer it was considered that in-flight decontamination by the extreme radiation in Jupiter's belts may be an option that could be explored.

3.3 Space mission considerations

Monitoring of the radiation belts through one or more orbiters is necessary for their comprehensive exploration. Several mission concepts are outlined, each one for different mission cost levels (L- or M-class). A third flyby or short-duration, low altitude orbiter mission option is described as a target-of-opportunity or a pre-cursor to options (1) and (2) (Fig. 8). Any of the three scenarios would benefit from coordinated Earth-based monitoring of the jovian system (Table 1). For any of the mission concepts, international collaboration may reduce ESA's contribution and depending on the level of involvement the cost-category of a mission scenario may change. All concepts are principally feasible on solar power, although other options involving space nuclear power [166] may potentially allow for extra flexibility in mission design.
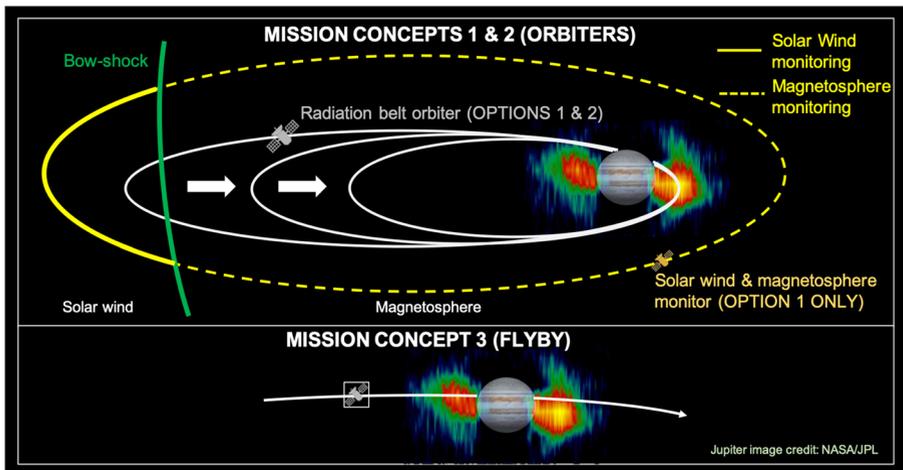
Fig. 8 Simplified sketch for orbiter mission concepts "1" and "2" (top). Option "3" (flyby or short-lived, low altitude orbiter) is shown at the bottom panel. Distances shown are not to scale

Option 1: Radiation belt orbiter and Solar wind/magnetosphere monitor Covering all science goals identified in Section 2 requires synergistic investigations by a minimum of two orbiters. For the minimal configuration we consider that a primary spacecraft performing regular radiation belt crossings carries the in-situ particles and fields instrumentation suite, while a smaller spacecraft monitors the upstream solar wind and the magnetosphere globally.

The primary spacecraft's orbit should be highly elliptical, similar to Juno's ($\sim$53 days period), to minimize crossing durations through the belts and exposure to radiation, but more equatorial so as to sample the radiation belts at their core. As both Juno and Cassini investigations already demonstrated, belt crossings lasting several hours each are more than sufficient for collecting excellent quality observations and for resolving radiation belt structuring down to $\sim 10^{-2}$ planetary radii thanks to the high-time resolution sampling that is possible for all particles and fields instruments [75, 140]. As the mission evolves, the eccentricity and the period of the orbits could be reduced so as to achieve more frequent belt crossings and capture shorter variability time scales. Excursions in local time and latitude could be performed as the apojove reduces, e.g. through Callisto flybys, like it will be done for JUICE, or with spacecraft resources, if possible. Latitudinal excursions could regulate the rate of ionizing dose accumulation as the belt crossings are becoming more and more frequent.

The secondary spacecraft, carrying a lightweight in-situ particles and fields suite and remote sensing instruments (e.g. [43]), should be placed in an orbit extending upstream of Jupiter's bow-shock ($\sim$100 R_J) from where solar wind monitoring is possible for extended periods. Its perijove could be outside Callisto's orbit to limit radiation exposure. Closer to the magnetosphere, ENA and X-Ray imaging becomes possible, along with simultaneous two-point measurements with the primary orbiter. If only one imager can be accommodated, an ENA camera would be preferred if all the other remote sensing methods that can be executed from Earth (Table 1) are available. X-ray imagers offer otherwise excellent remote sensing options, as they may probe simultaneously the electron belts, the aurora, and the Io torus [21, 42, 45, 124].

Option 2: Radiation belt orbiter The M-class variant is similar to the L-class but does not include the solar wind/magnetosphere monitoring spacecraft. Most science goals that depend on solar wind monitoring, are affected. Losses can be partly mitigated by propagating solar wind parameters from 1 AU. Close-proximity ENA or X-Ray imaging and two point in-situ measurements in the magnetosphere may not be replicated, unless any of these imagers can be accommodated on the primary spacecraft. The advantages of a single orbiter are that mission design and operations would be simpler, while significant mass allocation could become available for instrument design, radiation shielding, or other critical mission subsystems. This variant retains a great discovery potential, given the existing gaps in spatial and temporal coverage of Jupiter's radiation belts as well as missing measurements (Section 1.3).

Option 3: Flyby or short-duration orbiter Due to its strong gravity, Jupiter is regularly used as a swing-by target for adjusting a spacecraft's trajectory towards its Solar System destination. Many mission concepts target the Jupiter system itself. A Cubesat

or Smallsat-sized probe riding along with the main spacecraft could be released for a flyby through the belts' core. For such a small resource mission, observations should prioritize measuring the least defined parameters, i.e. suprathermal ion charge states, electrons up to ~100 MeV, protons up to ~1 GeV and ion composition at least up to 100 MeV/n. Observations from such a flyby mission could provide key input for science goals 2.2, 2.3, and 2.6, further constraints to all others and refine the requirements for Options 1 and 2. Should resources allow, a small, short-lived orbiter with frequent crossings through the belts' core can be considered instead. Such low resource missions can be successful: Data from the Colorado Student Space Weather Experiment CubeSat in Earth's radiation belts, for instance, led to the discovery of the decades-sought, trapped CRAND electrons [85, 86].

3.4 Enabling technologies

Miniaturization of relativistic charged particle detectors For the high energies considered in Jupiter's radiation belts (~100 MeV electrons, ~GeV/(n) ions), particles are both penetrating and fast. Methods measuring time-of-flight or energy losses on silicon detector stacks either don't work or give poor constraints to a particle's energy, e.g. above 100-200 MeV for protons. A most efficient method to resolve energy, species, and ionization state of such particles is magnetic spectrometry, used until now in planetary radiation belts but for electrons in the keV to low MeV range (e.g. [16, 81]). Existing detectors that use it for higher energies are very power consuming and heavy (many 10s of kg or more) partly due to the application of large permanent magnets [132] and partly because they are designed to detect low flux, ultra-high energy GCRs. A step towards miniaturizing such instruments for planetary applications is the MiniPAN (Mini-Penetrating Particle Analyzer) detector [180], a modular magnetic spectrometer (mass <10 kg, power <20 W) that may perform ion composition and electron spectrometry measurements up to several GeV(/n) (Fig. 9). A demonstrator was approved for development through a European Union Future and Emerging Technologies program, but a Jupiter-specific design would require further studies.

The energy limit to which magnetic spectrometry can be applied for resolving heavy ion ionization states remains to be investigated. Non-magnetic spectrometers for ultrarelativistic electrons developed in Europe, such as HEPD that is operating on the China Seismo-Electromagnetic Satellite [1], use silicon detector stacks and calorimeters. The large mass of all aforementioned detectors may be reduced by adjusting their geometry factor to the orders of magnitude stronger MeV electron and ion fluxes at Jupiter compared to that of GCRs (Fig. 1). Additionally, such instruments reconstruct the 3D trajectory of the measured particles by tracking them on large, successive detector planes of silicon strip detectors. With an instrument on a spinning spacecraft (Section 3.1) tracking becomes two-dimensional, which may also allow to reduce its total mass as slit-shaped detectors can be accommodated in smaller volume.

Electromagnetic cleanliness For magnetic spectrometry to capture the energies of particles in Jupiter's radiation belts, permanent magnets should generate static fields
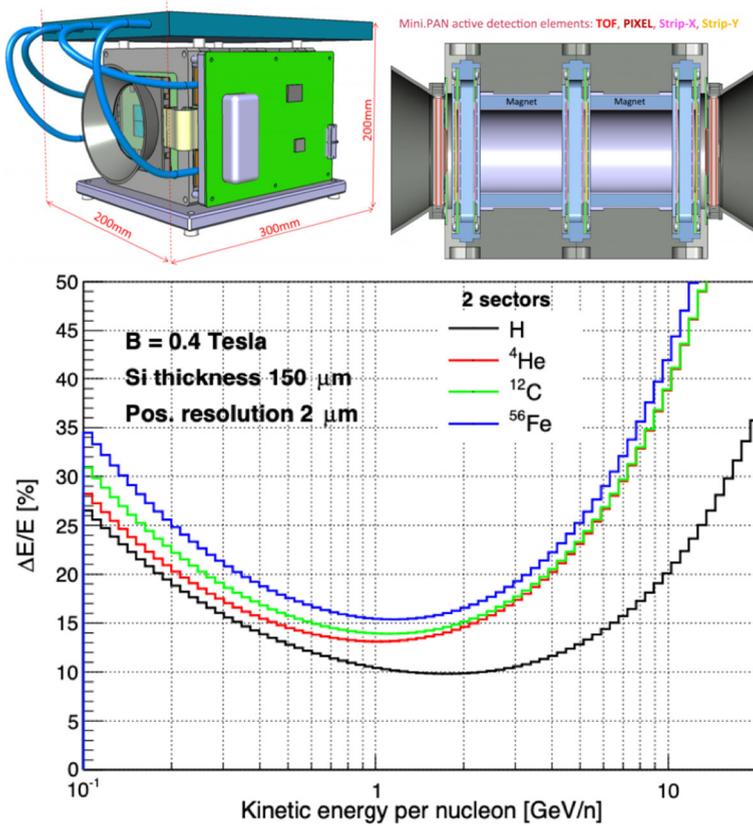
Fig. 9 (Top panels) Simplified schematic of a double-sided MiniPAN instrument concept. (Bottom) The estimated energy resolution as a function of ion kinetic energy, for different ion species. Images are from https://www.unige.ch/dpnc/index.php?cID=947 and more information is available in [180]

that may have to be several times stronger than what has been used e.g. on the LEMMS instruments of Cassini and Galileo (∼0.06-0.08 T) [81, 173] or the MagEIS instrument of the Van Allen probes (∼0.15 T) [16] or be considerably larger in size. Strong stray fields from permanent magnets can interfere with plasma detectors or magnetometers that are essential for any radiation belt focused mission. The trade-off between the maximum energy resolved (determined by the magnet strength and size), the strength of the stray fields and instrument mass should be considered. Instrument accommodation and design, e.g. choice of materials for the permanent magnet and for magnetic shielding, play a role.

Radiation hard electronics and detector performance The JUICE mission is designed such that the Total Ionizing Dose (TID) experienced by its most sensitive electronics contained in heavily shielded vaults would not exceed 50 krad by the end of the mission [46]. This tolerance level should be increased for a dedicated radiation belt mission. In addition, developing efficient active shielding systems for particle

detectors (e.g. anticoincidence or positive coincidence) that would reject counts from high fluxes of penetrating MeV electrons and protons in Jupiter's belts, should be investigated. Low energy electron detectors (<10 keV) are the most challenging for using anticoincidence [e.g. [102]], as techniques like Time-of-Flight, cannot be applied, and other coincidence schemes should be explored. The use of Faraday Cups as on Europa Clipper, which are less sensitive to high energy radiation, offer a solution for the measurement of low energy particles [172]. Both the high-resistant electronics and active shielding techniques, would reduce the requirements for passive spacecraft shielding as the way to achieve a good signal to noise ratio, allowing to allocate mass in other subsystems.

Energetic Neutral Atom imaging (>1 keV) ENA imaging is considered in the payload concept described in Section 3.1. JUICE will be first mission to perform a dedicated study at Jupiter in low and high energy ENAs [61]. Still, detectors for >1 keV ENAs (INCA on Cassini, JENI on JUICE) [111], have been or are being developed only outside Europe. Developing high energy ENA capabilities would enable more flexibility in mission planning and open new roads for scientific applications in Earth's magnetosphere, comets, and the heliosphere where ENA imaging is applicable [20, 42, 103].

4 Jupiter radiation belt science in context

4.1 Jupiter exploration

Following the exciting discoveries by the Galileo mission at Jupiter, JUICE and Europa Clipper were designed in response. Besides exploring Europa, Ganymede, and Callisto in detail, these missions will carry instruments that offer an interdisciplinary view of the jovian system, including its magnetosphere and the outer radiation belt regions. Similarly, new discoveries by Juno, which has been extended through September 2025, are revealing the complexity of the jovian magnetosphere and its energetic particle environment, already generating many new questions (Section 2.4). These missions, along with campaigns by Earth-based observatories, would shape our views about Jupiter until about 2035 (Fig. 10). Beyond 2035, a mission that may explore Jupiter's magnetospheric environment has been announced by China, with arrival probably after 2036, but with no further details known [25]. A space mission, picking up from where Juno, JUICE and Europa Clipper take our understanding, will continue the exploration of the giant planet, which has been regular since Pioneer 10 and 11 (Table 1). Jupiter exploration has also benefited from the synergy of space missions and Earth-based observatories. The prospects for the development of new observatories after 2035 are still unclear.

4.2 Multi-spacecraft investigations of planetary magnetospheres

Over the last two decades, terrestrial magnetospheric science has benefited greatly from space missions utilizing several spacecraft for simultaneous, multi-point
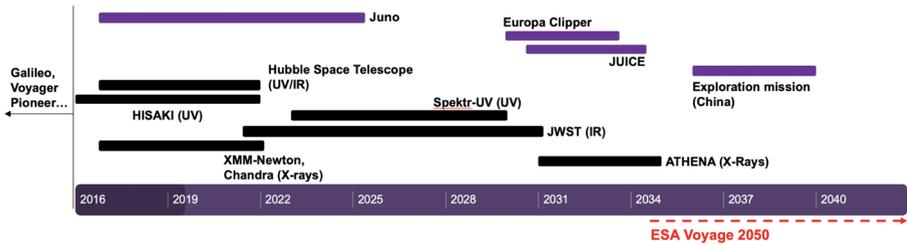
Fig. 10 The timeline of missions relevant to Jupiter's magnetosphere and radiation belts (magenta: space missions; black: Earth-based observatories that can target Jupiter). Ground-based, synchrotron radiation belt or IR, jovian aurora observations are assumed to be available throughout this timeline. The timeline for China's exploration mission is tentative. For other future missions, timelines indicate the anticipated period of science operations. As of January 2021, Juno has been extended until September 2025

measurements of the geospace, in addition to the regular monitoring of the upstream solar wind and of the various geomagnetic indices which has been going on for even longer. Missions like Cluster, Double Star, THEMIS, Magnetospheric Multi-Scale (MMS), and the Van Allen Probes have drastically changed the way we understand Earth's radiation belts, as part of the terrestrial magnetosphere (e.g. [47]). The findings from the Van Allen Probes, in particular, have led to many breakthrough discoveries and have evolved the state of the art of radiation belts' research to a new level [8, 126, 156, 163]. The remarkable increase of refereed publications on the subject after 2000 (Fig. 11) and the launch of follow-up missions like Arase, the China Seismo-Electromagnetic Satellite, Lomonosov, and others [1, 112, 155], are representative of the aforementioned, rapid progress and increased interest in the field (see also Appendix 1). Multi-point measurements of space plasma interactions in our Solar System have become a norm: The two ARTEMIS spacecraft investigate the lunar-solar wind interaction since 2010 [64], while BepiColombo will do the same at Mercury [14]. The recently funded ESCAPADE mission will be the first dedicated two-orbiter mission to study the Mars-solar wind interaction [87]. Similarly, ESA's Comet Interceptor will perform two-point measurements of a comet's plasma environment [69]. As it stands now, no coordinated multi-spacecraft mission is planned for any outer planet magnetosphere, but it is the essential and obvious way forward. A mission to explore Jupiter's radiation belts (Section 3.2) would have an enormous potential for discoveries, not only because it could be the first to investigate Jupiter's magnetosphere with multiple spacecraft, but also because it would focus on one of its least sampled components.

4.3 Comparative studies

Jupiter radiation belt science is well aligned with the continuous investigations of Earth's radiation belts by numerous ongoing missions, and the fact that many White Papers in response to ESA's Voyage 2050 call focus on charged particle acceleration and energy transfer between plasmas and fields. Thanks to the extensive exploration of Saturn's radiation belts by Cassini and the continuously growing set of measurements by Juno at Jupiter, a large volume of high-quality observations is being
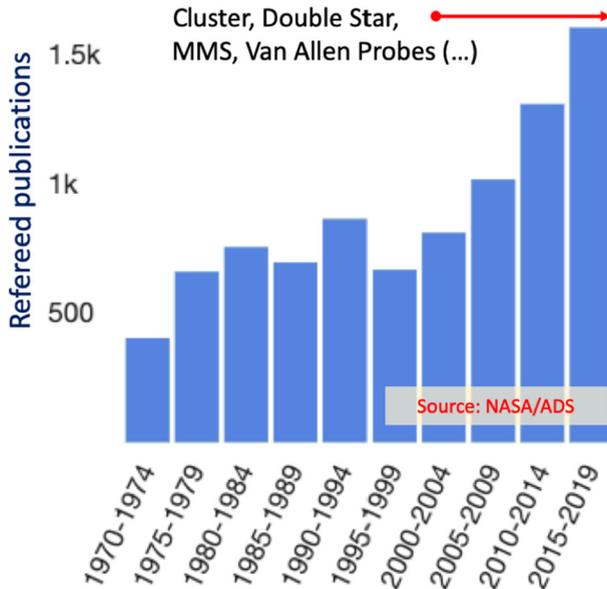
Fig. 11 Number of refereed publications on energetic charged particles and/or the radiation belts of Earth between 1970 and 2019 from https://ui.adsabs.harvard.edu/. Created with the command: *abs:(((radiation belt) OR (energetic particles)) NOT Jupiter NOT Saturn NOT Uranus NOT Mars NOT Mercury NOT Neptune AND Earth) AND year:1970-2019*

generated covering many years and different radiation belts, enabling detailed comparative studies for the first time. Planned or ongoing missions would add to that: the limits of radiation belt formation can be exploited with BepiColombo at the weakly magnetized Mercury, and with JUICE at Ganymede's mini-magnetosphere [49]. Potential extension of such observations to Uranus or Neptune [52, 74] would allow us to explore radiation belts across a variety of environments and scales. X-ray telescopes, following their application on the SMILE and BepiColombo missions [14, 21], will become readily available for Jupiter spacecraft and open a new era in the exploration of planetary magnetospheres.

4.4 Opportunities for interdisciplinary science investigations

Magnetospheric and Jupiter system science A mission designed for radiation belt studies is suited to explore any other magnetospheric region it crosses. The mission concepts considered (Section 3.3) are sufficient to extend and/or complement many of the magnetospheric science goals of Galileo, Juno, JUICE, and Europa Clipper [6, 61, 127]. The option for coordinated, multi-point measurements could be a first for a giant planet's magnetosphere, with obvious advantages (Section 4.2). The strong coupling between the radiation belts and Jupiter offers many opportunities to study different components of the jovian system, besides what is described in Section 2.6. For instance, Juno data show that Jupiter's internally generated magnetic field has changed in the time between Pioneer 10 and 11 observations and today [32, 114].

The observed variations, attributed to advection of the field by Jupiter's zonal winds, could be further monitored with a radiation belt mission reaching to low jovian altitudes two decades after Juno. Potential close moon flybys offer a chance to conduct new type of measurements: the detection of high energy albedo particles from moon surfaces, released due to the precipitation of very high energy ions, is an example. Such particles, recently detected at Earth's Moon, offer insights on the physical properties of the immediate subsurface [148, 176].

Heliospheric physics ENA imaging offers opportunities to explore the formation, interactions, and the large-scale structure of the global heliosphere, providing insights on the plasma processes at ∼100 AU and beyond. Relevant investigations by the Interstellar Boundary Explorer (IBEX) and Cassini/INCA have already revolutionized our notions about the global heliosphere [42, 82, 103], established an increasingly growing community and new missions either in preparation (IMAP [104]) or in consideration (Interstellar Probe [106]). Potential measurements by an ENA imager at Jupiter would extend the time history of previous measurements. Regular GCR observations and a detailed view of escaping relativistic electrons from Jupiter, offered by the mission's energetic particle detectors, when combined with similar observations at 1 AU, would update models of particle transport in the heliosphere [170].

Astrophysics Jupiter offers many astrophysical parallels (Section 1.3). While detections of magnetized exoplanets are increasing [114], no exoplanetary radiation belt synchrotron emissions have been detected, possibly due to their weak intensity and the large distance from Earth. Predictions about the radiation environment of exoplanets may thus rely on our understanding of radiation belts in our Solar System. Radiation belts can be part of any strongly magnetized object, not just of (exo)planets. Ultra-cool brown dwarfs (UCBD) appear to host magnetospheres resembling those of our Solar System. Radio emissions of the UCBD NLTT 33370B not only have similarities to those emitted from Jupiter's radiation belts, but also seem to indicate that the object's magnetosphere has a magnetodisc-like configuration with a dense plasma torus, another striking similarity with the giant planet [174, 175]. Understanding the processes at work in Jupiter's radiation belt can also inform the study of rotating radio transients which may originate from particle scattering within pulsar radiation belts [89]. Finally, in-situ measurements at Jupiter offer insights on how a strong charged particle accelerator can seed its surrounding environment with particle radiation. The study of Jovian Cosmic Rays, i.e. energetic electrons and ions escaping into the heliosphere [91, 170], in conjunction with similar studies at other planets [83, 94] could update models of how this escape develops with implications about "local cosmic ray" sources in different astrophysical systems.

Radiation belt environment models Jupiter's mini-Solar System is a very attractive target for many exploration missions. For any of these, considerations of Jupiter's radiation environment are always a high priority. Radiation environment models, bound to the existing data limitations, have uncertainties (e.g. [48]) that could propagate into mission design in the form of extra shielding mass (or less payload mass).

A comprehensive in-situ investigation of Jupiter's radiation belts would support empirical radiation belt model design and offer opportunities to optimize the future exploration of the jovian system and many of its rings and moons are contained within its harshest energetic particle environment.

5 Summary

Jupiter's radiation belts are a major component of the planet's magnetosphere, but the unprecedented scale, complexity and energetics make their measurement very demanding. Their severe energetic particle environment has challenged, and still challenges, their in-situ spacecraft exploration. However, the outstanding science that can be performed through their in-situ study should motivate us to overcome these hurdles and plan for their comprehensive survey. The Juno mission has passed repeatedly through Jupiter's belts and has shown this to be a feasible technical task. Experience gained from the JUICE mission, and the highly anticipated results of its scientific investigations, will pave the way for the next step in the exploration of the jovian system by ESA. In this article, originally a White Paper submitted in response to the European Space Agency's call for science themes for its Voyage 2050 programme, we have argued why a multi-spacecraft mission to Jupiter's radiation belts should be that next step. A first multi-spacecraft mission to a giant planet's magnetosphere and radiation belts lends itself to numerous important discoveries, as the extraordinary success of ESA's Cluster mission, a similar "first", has proven. The interdisciplinary character of the investigations that can be performed in Jupiter's system will only increase the mission's impact further. We therefore believe that Jupiter's radiation belts deserve to be assigned as a high priority target in the Voyage 2050 programme cycle and we urge ESA to conduct and support the necessary mission, instrument, and technology studies that would eventually make their in-situ exploration a reality.

Appendix 1: Full list of coauthors and endorsers

This article is based on a White Paper submitted in response to the European Space Agency's call for science themes for its Voyage 2050 programme. In addition to the 29 authors of the White Paper, many more scientists have contributed to and/or endorsed its content and that of a similar White Paper [119] since its original submission . The full list of 97 scientists from 16 countries is provided below in alphabetical order:

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Declarations

Conflict of Interests The authors declare that they have no conflict of interest.

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